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PARAMETERS THAT AFFECT THE ACCURACY AND SETABILITY OF A MAGNETIC FIELD IN AN IRON CORE ELECTROMAGNET*

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Introduction

It is a well established fact that knowledge of the excitation current alone is not sufficient to allow one to predict the induction in a particular magnet. Other parameters such as temperature and previous history of induction are essential to the determination. As has been pointed out recently[1,2] the time rate of current excitation is an important parameter and must also be considered.

A detailed study of the magnitude of these effects has been made not only on the induction but on the line integral of induction over a path through the magnet, the latter being more important in the case of beam transport type magnets. In addition, a comparison between solid core and laminated magnets and between large solid core and small solid core magnets was made.

It has been shown that the distribution of induction over the magnet pole is a function of excitation rate as well as excitation for magnets that are partially saturated. The location in the magnet where the induction is measured may therefore be important. The effects of previous history of induction on the setability of these magnets is also discussed.

Temperature Dependence and Previous History

The temperature dependence of $\int B d\ell$ and B in a magnet can be analyzed by using the simple model of a typical H core magnet such as Fig. 1. If one assumes the coefficient of linear expansion $\alpha = \frac{\Delta\ell}{\ell} / C^\circ$, then for a gap width "d" of the magnet

$$\Delta d = \Delta T \alpha d \quad \text{expansion}$$

In the linear portion of the magnetization curve this change in gap $\frac{\Delta d}{d}$ will result in a change in field $-\frac{\Delta B}{B_o} = \Delta T\alpha$. The total lineal expansion of the magnet in length is $\Delta\ell = \Delta T\alpha\ell$. The difference in $\int_{-\infty}^{+\infty} B d\ell$ for a variation in temperature ΔT is

$$\Delta\int_{-\infty}^{\infty} B d\ell = \int_{-\infty}^{\infty} (B+\Delta B)\, d(\ell+\Delta\ell) - \int_{-\infty}^{\infty} B d\ell$$

if we let

$$\int_{-\infty}^{\infty} B d\ell = B_o L_{\text{effective}}, \quad \text{then} \int_{-\infty}^{\infty} (B+\Delta B)\, d(\ell+\Delta\ell) = \int_{-\infty}^{\infty} B d\ell + Bd\,\Delta\ell + \Delta B d\ell + \Delta B d\,\Delta\ell$$

$$= B_o L_{eff} + B_o \Delta L_{eff} + L_{eff}\Delta B + \Delta B\, \Delta L_{eff}$$

now $\Delta B\, \Delta L_{eff} = \Delta T^2 \alpha^2 BL$ can be neglected.

Therefore

$$\delta \int_{-\infty}^{\infty} B d\ell = B_o L_{eff} + B_o \Delta L + L\Delta B - B_o L_{eff}$$

$$= B_o \Delta L_{eff} + L_{eff}\, \Delta B$$

$$= B_o \Delta T\, \alpha\, L + L(-\Delta T\, \alpha\, B_o) = 0$$

therefore $\int_{-\infty}^{\infty} B d\ell$ is independent of temperature.

Now, if we are in the region where $\frac{\Delta d}{d} \approx .90\, \frac{\Delta B}{B}$ (10% saturation) the decreasing field and the increasing magnet length fail to cancel each other by 10%. In this case

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[1] J. K. Cobb and C. Harris, Proceedings of the International Symposium on Magnet Technology, 1965, p. 823.

[2] F. M. Harris, A. Delizee, W. C. Middelkoop and B. de Raad, CERN ISR-BT/66-26.

the actual $\delta \int_{-\infty}^{\infty} B d\ell = 0.1 \, \Delta T \, \alpha \, L_{eff} B_0$ and for $\Delta T = 30°C$, $\delta \int_{-\infty}^{\infty} B d\ell = 0.003\%$. The effects of past history of magnetization on the induction of an electromagnet are rather well known, especially the effects of residual field. In the cases discussed here, where reproducibility of induction was of paramount importance the magnets were degaussed prior to each measurement. The method of degaussing used will be described in the section on the actual tests made.

Experimental Procedure to Determine the Effect of Run-up Rate on B and $\int_{-\infty}^{\infty} B d\ell$

The object of the experiment was to determine the effects of run-up rate on the setability of a magnet using only a knowledge of the current. The tests were performed on three different magnets: One large 3-meters long, H-type magnet with solid core and poles; one small 1/2-meter long H-type magnet with solid core and poles; and one 1-meter long H-type magnet with laminated core and poles. All three were similar to Fig. 1.

Of particular interest on the large H-type magnet was the differences in B and $\int_{-\infty}^{\infty} B d\ell$ for run-up rates of 3, 6 and 9 amperes/sec (since this was the general run-up rate range for which these magnets would be energized). To insure identical conditions between each test the measurements were started from the degaussed state. Degaussing was achieved by running the current up to power supply maximum, down to zero and reversing the power supply. A predetermined amount of reverse current was fed into the magnet and held for 30 seconds and then run down to zero. A field measurement was made each time to determine that the remnant field really was lower than 1 gauss (which was our definition of a degaussed state). The measurements of $\int_{-\infty}^{\infty} B d\ell$ and B_{max} were made at four different levels of excitation, namely 200, 400, 600 and 800 amperes, after arriving at that excitation current via each of the three rates.

On the smaller solid core and pole magnet, it was only possible to excite the magnet to 14 amperes but it was possible to excite it using many different rates of current excitation. In this magnet 14 amperes corresponded to ≈2800 gauss.

In order to make direct comparisons between the magnets, the run-up rates were expressed in terms of gauss per second rather than amperes per second since the relationship between amperes and gauss is different for each magnet. Thus 3, 6 and 9 amperes per second on the large magnet correspond to 60, 120 and 180 gauss per second whereas the same rates on the small magnet correspond to 600, 1200 and 1800 gauss per second. Measurements were taken on the small magnet at much lower current excitation rates for direct comparison with the large magnet.

Since the object of the experiment was to find out how B_{max} and $\int_{-\infty}^{\infty} B d\ell$ behaved with different run-up rates, all measurements were normalized to the 120 gauss per second rate. Figure 2 shows how the induction at the center of the magnets varies with run-up rate over the range from 40 gauss per second up to 5400 gauss per second for the small magnet (B-003) excited to 3000 gauss and for the large magnet (B-300) excited to four different levels, 4000 gauss, 8000 gauss, 12,000 gauss and 14,500 gauss. It can be seen from Fig. 2 that the two magnets behave in a very similar manner, their agreement being quite striking in the region below 12 kG. In general, it is seen that a higher rate of excitation results in a higher induction than the lower rates of excitation. Over the range from 100 to 1000 gauss per second the difference in B_{max} is about 0.2%.

Figure 3 is a graph of deviation of $\int_{-\infty}^{\infty} B d\ell$ similarly plotted against run-up rates for the two magnets, and it can be seen that the agreement is quite good with the deviation of B_{max}. This would indicate that the distribution of B through the magnet is nearly constant.

Measurements were made to thoroughly test this conclusion on the large magnet only. Using a nuclear magnetic resonance fluxmeter point measurements of induction as a function of longitudinal position in the central plane and at the transverse center of the magnet were made. These results are shown in Fig. 4. All measurements of B_{max} were normalized to that B_{max} achieved after using the 120 gauss per second rate which is the zero deviation axis in Fig. 4. It can be seen from Fig. 4 that as the magnet nears saturation the deviation of B with run-up rate is less than when the magnet is not saturated. In addition the deviation of B along the length of the magnet is no longer a constant.

The measurements that were made on the laminated magnet showed absolutely no deviation of either B or $\int_{-\infty}^{\infty} B d\ell$ with run-up rate, indicating that eddy currents during the run-up rate in some manner are responsible for the deviations in B and $\int_{-\infty}^{\infty} B d\ell$.

Conclusions

As has been shown, when setting a solid pole and core magnet accurately to a particular value of induction using current readings alone it is very important to control the rate at which the magnet is excited. These effects are reduced in magnitude as one approaches saturation of the magnet.

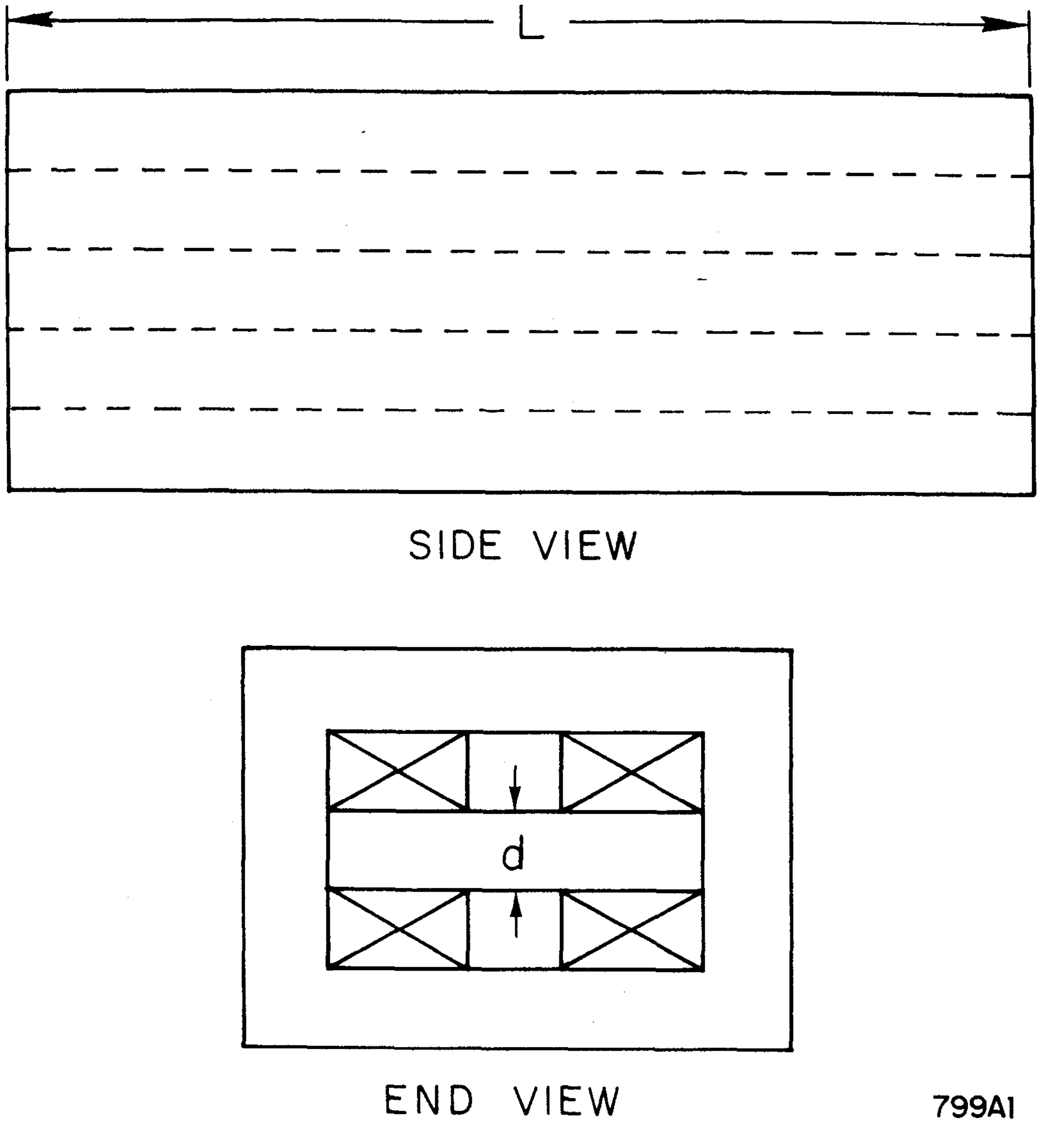

FIG. 1 -- H-TYPE MAGNET

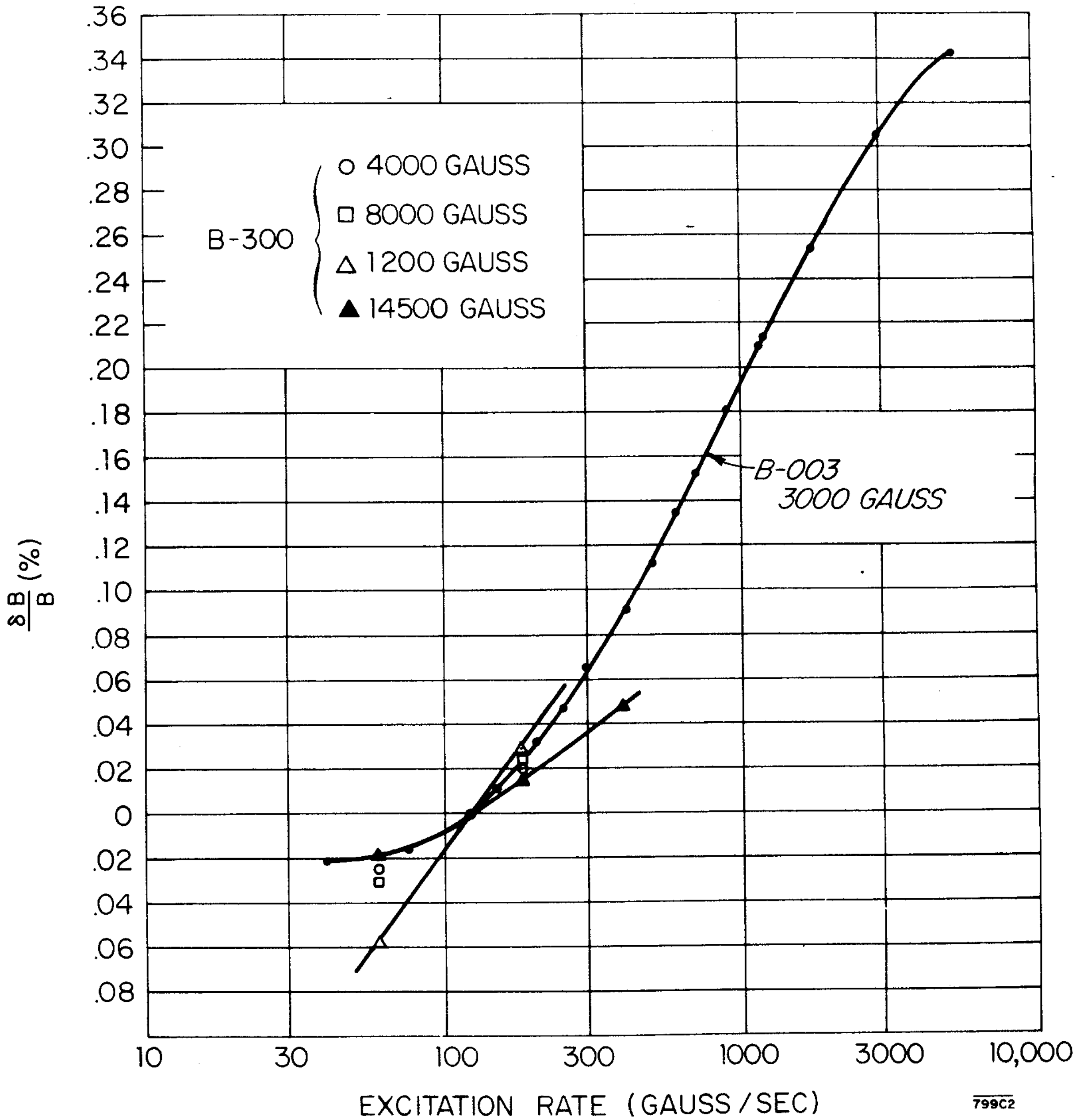

Fig. 2 - $\frac{\delta B}{B}$ vs RUN-UP RATE

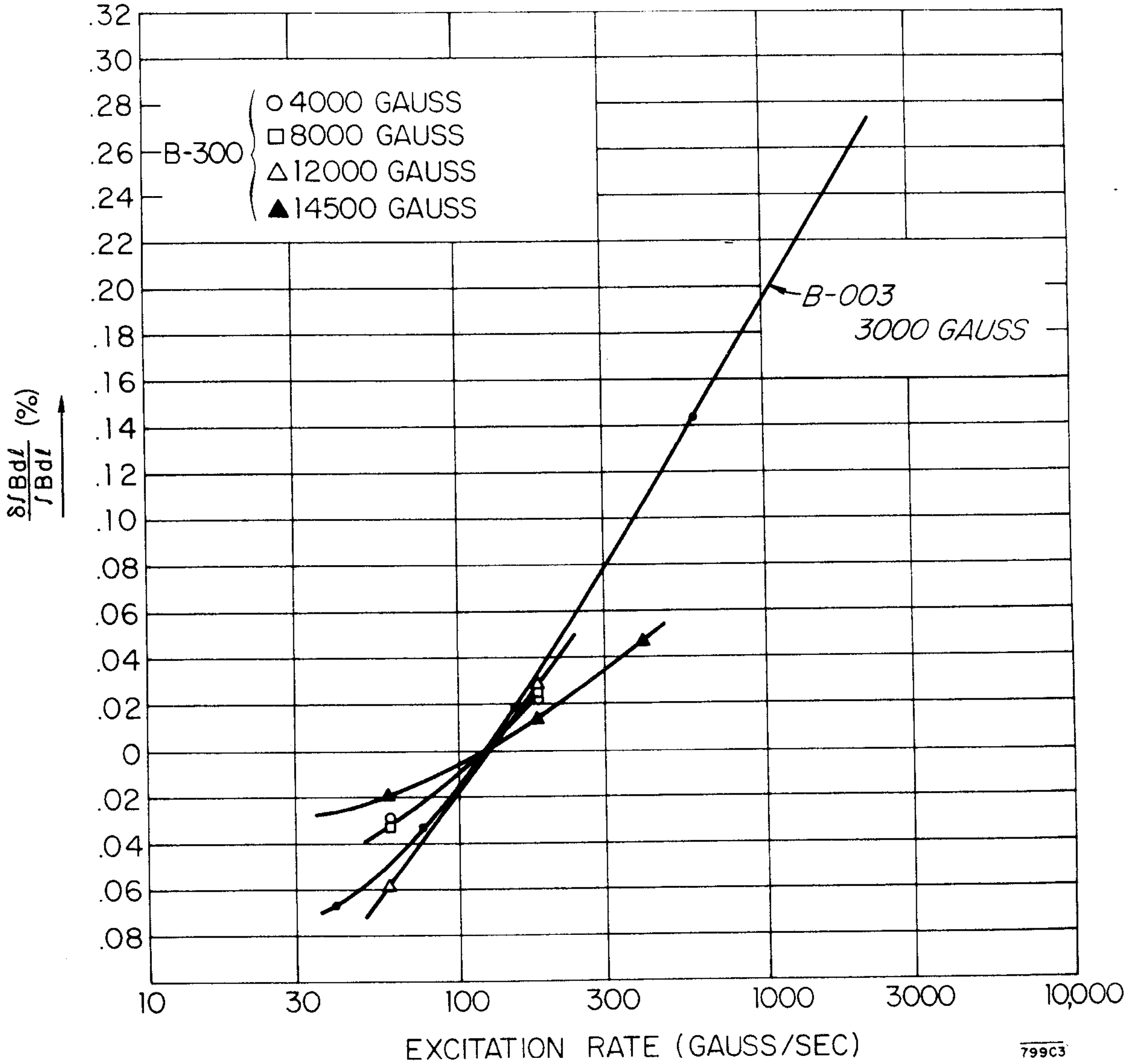

Fig. 3- $\frac{\delta \int B d\ell}{\int B d\ell}$ vs RUN-UP RATE

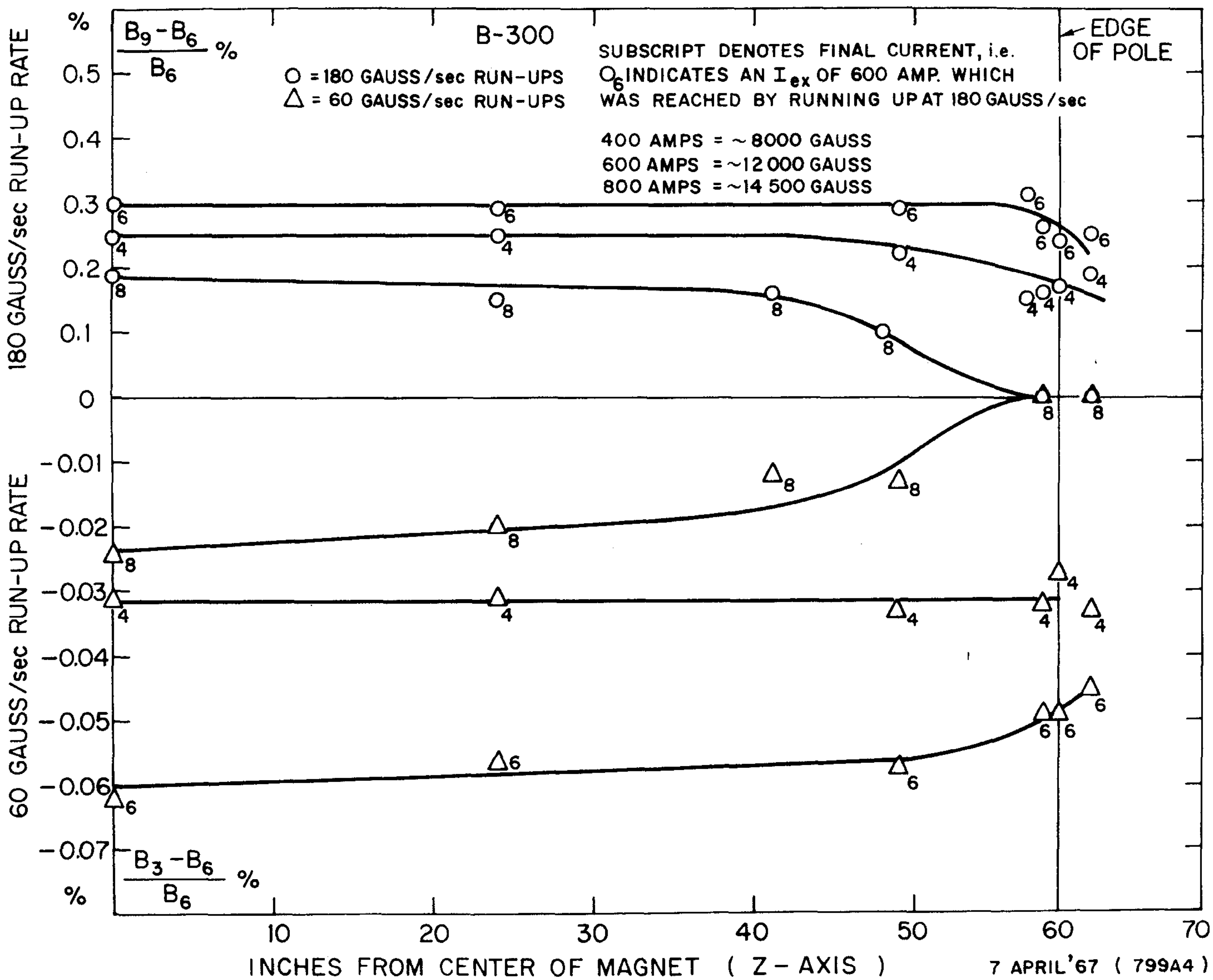

FIG.4 -- DEVIATION OF B WITH LONGITUDINAL POSITION AND RUN UP RATE